EUV Dark-Field Microscopy for Actinic Defect Inspection

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Introduction to EUV mask blank inspection

- Laboratory scale defect detection tools for mask blank inspection at 13.5 nm are highly demanded and crucial to the successful implementation of next generation EUV lithography;
- Substrate roughness and remaining particles of size 20 – 150 nm are critical for print circuit quality during wafer manufacturing;
- Aerial scanning tools (Zeiss AIMS at 157 nm) and phase measurement tools (Lasertec MPM at 157 nm) are available, but not for EUV;
- Amplitude defects as e.g. particles on top of multilayer mirror (ML) and phase defects inside of ML have to be detected and localized at the ML-defined wavelength (actinic), i.e. at λ = 13.5 nm.

Theory of defect detection

- (amplitude/phase) defects can be detected efficiently in dark field mode

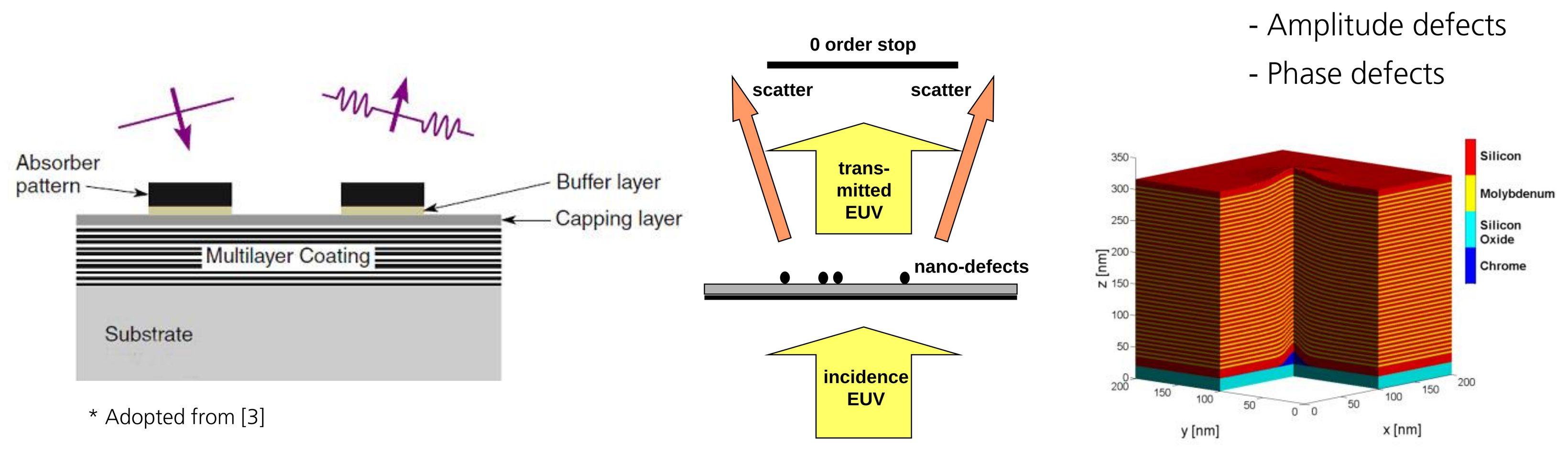


Figure 1. Sketch of patterned multilayer (left), scheme of dark field mode (middle) and model of defective multilayer (right).

- detection sensitivity is limited by different kinds of noise:

$$Signal = M \cdot n_{max} \cdot QE \cdot P, \quad \delta_{photon} = n_{max} \cdot \sqrt{QE \cdot P}$$

$$Noise = \delta_{total} = \sqrt{\delta^2_{readout} + F^2 \cdot M^2 \cdot (\delta^2_{dark} + \delta^2_{CIC} + \delta^2_{photon})}$$

$$\frac{Signal}{Noise} = \frac{n_{max} \cdot QE \cdot P}{\sqrt{F^2 \cdot (n^2_{max} \cdot QE \cdot P + N_{dark} + \delta^2_{CIC}) + \delta^2_{readout}/M^2}}$$

- sensor readout noise (crucial if fast readout is needed)
- amplification: gain M; noise factor F (additional noise)
- dark (thermal) noise (temperature and time dependent)
- spurious noise (clock induced charge (CIC), small)
- photon induced noise (noise from signal itself)
- n_{max} = hν/3.7eV ~ 25 e⁻/ph at 13.5 nm

A reasonably high level of confidence of signal detection requires photon induced noise be higher than others:

$$P \geq \frac{\delta^2_{readout}}{n^2_{max} \cdot QE} \sim 1$$

The Rose criterion: Signal/Noise ≥ 5 needed for 100% certainty in distinguishing image features:

$$P > \frac{25}{QE} \sim 60$$

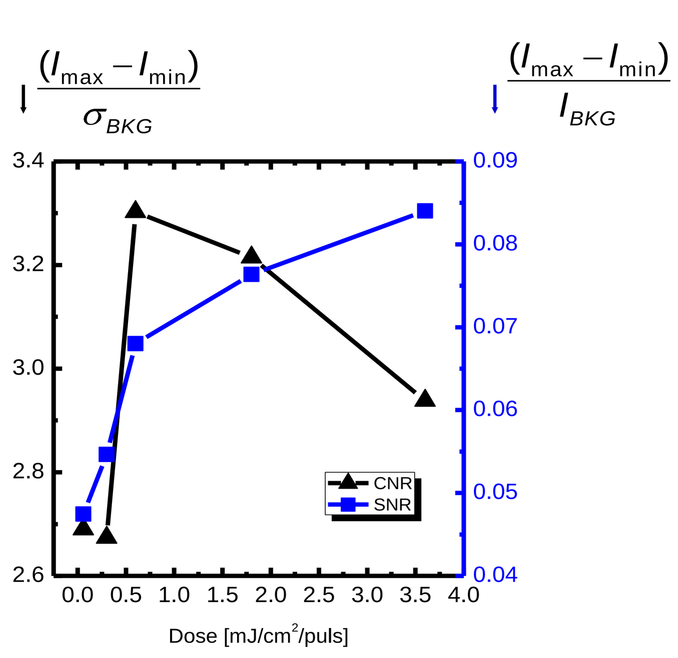


Figure 2. Image contrasts as function of irradiation dose in a case of high exposure times (several minutes, dominance of dark noise).

- estimation of source requirements:
  - Required irradiation dose (determined by detector sensitivity, magnification, transmission and defect scattering efficiency into objective solid angle) ~ 1 – 100 mJ/cm²;
  - Illumination slightly divergent;
  - Typical magnification ~ 20; Large object field ~ 500 – 1000 µm;
  - Scan speed 4 mm²/s @ 10 fps & 650 µm;

Source requirements:

- Used etendue ~ $1 \cdot 10^{-4}$ cm²sr ; Collection efficiency $\eta_{coll} = \Omega / 2\pi \cong 5 \cdot 10^{-3}$;
- Average radiance ~ 0.3 – 30 W/(cm²sr); ~ 1 W/2π (DPP, 1:1 imaging)

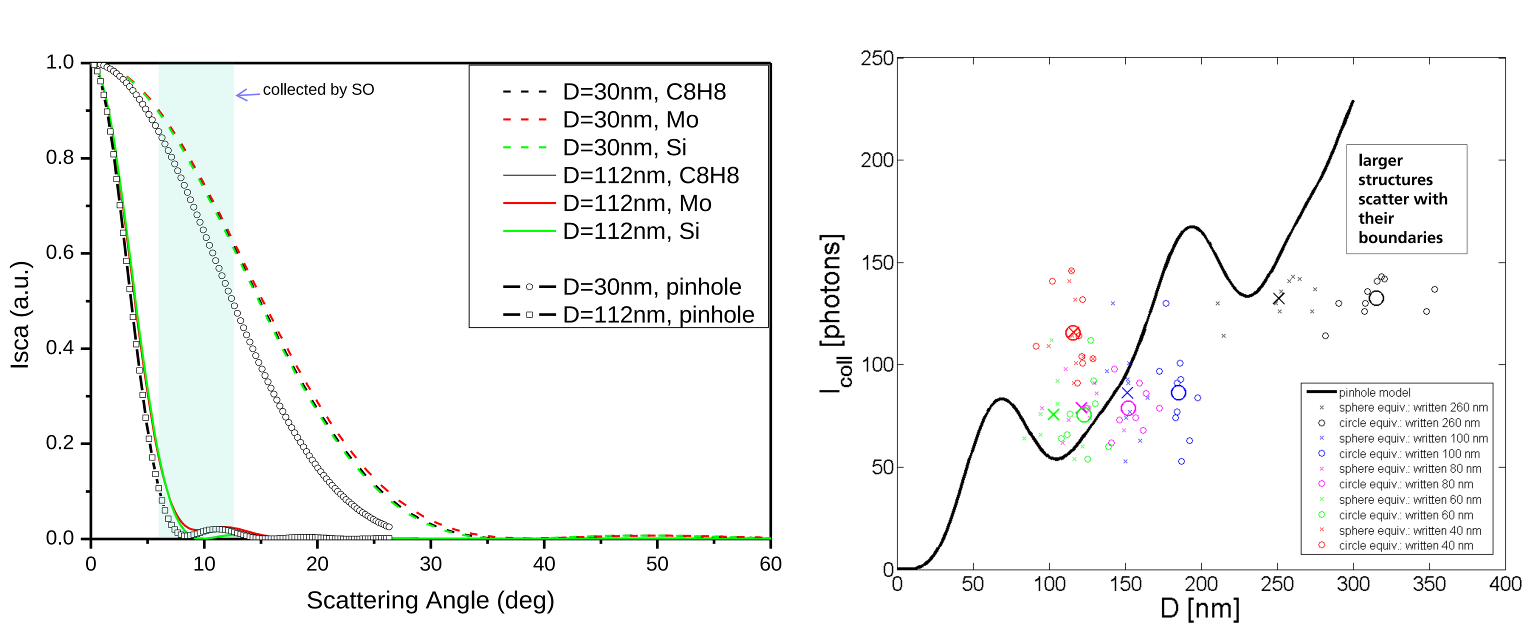
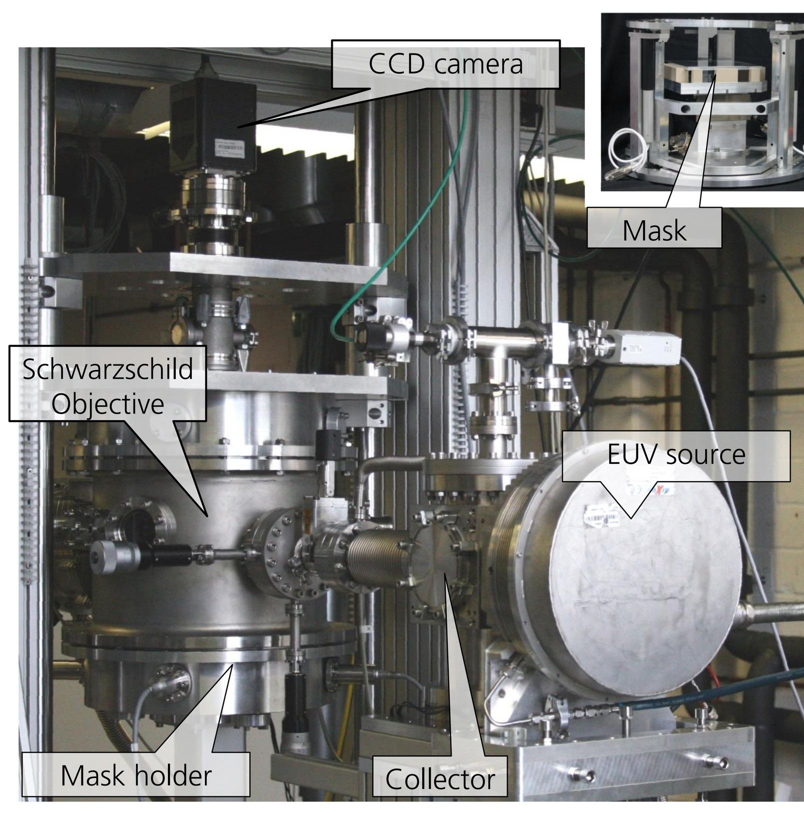


Figure 3. Comparison of Fraunhofer diffraction on pinhole vs. Mie scattering (left) and number of photons collected by CCD from a single defect - written pit structures of diameter *D* for irradiation dose of 1.6 *mJ/cm²* (all losses in the system are considered) in comparison with detected count numbers for certain defect sizes (effective diameters) (right).

Experimental setup

The experimental dark field reflection microscope based demonstrator for defect inspection has been successfully realized.



- central wavelength: 13.5 nm
- Xe-discharge source
  - ~ 0.5 mJ/sr/pulse/2%bw, 50 Hz
  - ~ diameter: 500 – 800 µm
- grazing incidence ellipsoid collector
  - $NA_{object,min}$=0.03, $NA_{object,max}$=0.04
  - $NA_{source,min}$=0.14, $NA_{source,max}$=0.16
- iris aperture, Zr filter, deflection ML mirror 45
- central stop => dark field operation
- mask blank holder and positioning (25 mm)
- FOV=650 µm, RES~600 nm limited by CCD (1024² pixel of size 13 µm, 1.1 fps, 10 e⁻/ph)
- Schwarzschild objective
  - 21x, focal length 27 mm
  - $NA_{object,min}$=0.11, $NA_{object,max}$=0.21
  - specified resolution 70 – 100 nm

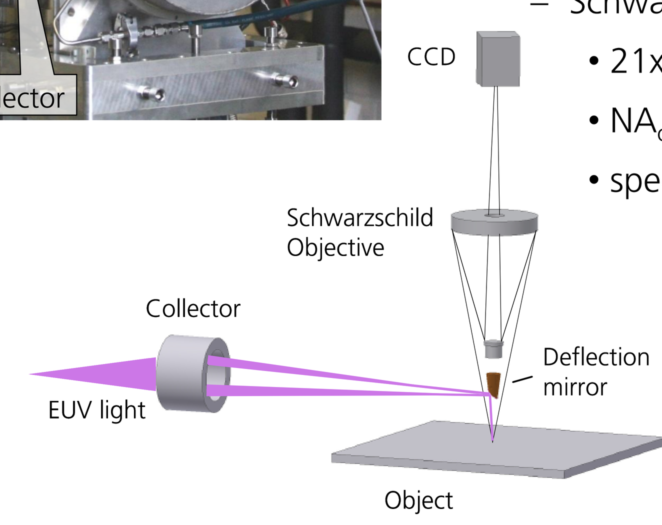


Figure 4. Photo of the EUV dark-field microscope for operation in reflection mode (left) with mask holder including 5-axis nanometer precision positioner (inset) and scheme of the setup (right).

Experimental results

- structured pits on a multilayer mirror:
- structured bumps on a multilayer mirror:
- natural defects on a multilayer mirror:

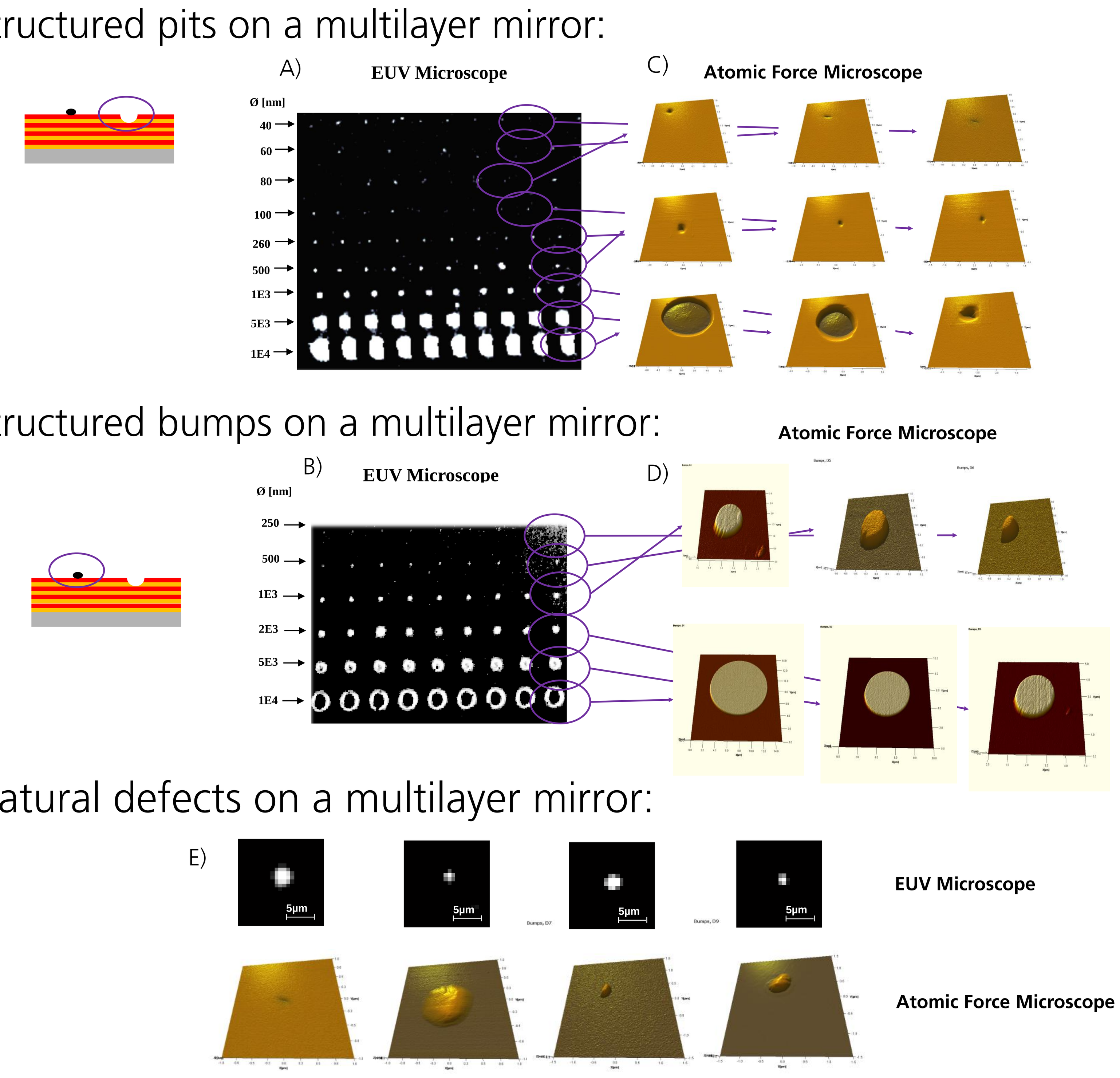


Figure 5. Dark field (DF) EUV image of structured ML mirror sample with (A) – structured pits, (B) – structured bumps; and (C, D) – corresponding AFM scans; (E) – examples of natural defects. Larger structures scatter from defect walls resulting in rings at the image.

Conclusions and outlook

- With limited resources and restriction to available components, we have accomplished first steps for a defect inspection concept.
- Programmed structures (pits and bumps) and natural defects on multilayer mirrors have been measured. Defect detection limits with a large field of view and moderate magnification were investigated in terms of required source photon flux and detection camera performance.
- We are confident that an economic solution for sub-30 nm sensitivity and acceptable throughput can be achieved in the next steps.